

# Practical application of Helicity to ICCs

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(Many thanks to R.Raman, S. Prager and M.Nagata for figures and to C.T. Holcomb, D.N.Hill, E.B.Hooper and B.W.Stallard for criticism)

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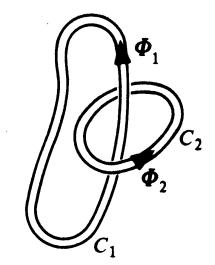
#### Helicity has application for predicting equilibrium, evolution and for discussing current drive.

- •Some theory
- •ICCs with use for helicity: the Spheromak, RFP and HI-ST
- •Asymmetries are a natural feature of relaxed/relaxing plasmas.
- •Current drive may be interpreted through using helicity.
- •The future?

# Helicity is used as a constraint to derive the field configuration of 'relaxed' plasmas.

•Unlike flux and energy, K = A.BdV - describes also field-topology: 'linkage'.

•Moffat: K=2 1 2 - linked flux-tube example.[1]



- •Woltjer: force-free fields:  $\times B = B = \mu_0 J$
- variational principle uses helicity as constraint to minimize magnetic energy.[2]

<sup>[1]</sup> Moffat, "Magnetic field generation in electrically conducting fluids", CUP, 1978

<sup>[2]</sup> Woltjer Proc. Nat. Ac. Sci. v44, no.6, p489, 1958

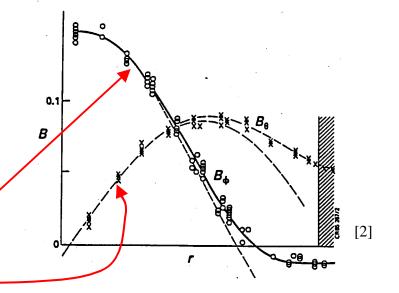
# Taylor employed helicity to determine field profiles of the RFP.

•Taylor: application to RFP

equilibrium: BFM solution to

 $\times$  **B**= **B** predicts field reversal:

$$\vec{B}_0 = B_0[J_1(r)\hat{z} + J_0(r)]$$



•Relaxation theory developed: any process by which the plasma will dissipate energy whilst conserving helicity - initially presumed to entail only MHD turbulence, but since found to entail long-wavelength fluctuations (linked to instability). [1]

# If equilibrium fields are close to force-free then helicity has application to the ICC.

ICC	Helicity	Taylor-	Vacuum	Helicity
		state?	field	input
Dipole	0	no	Strong	
Stellarator (torsatron)	1 2*	no	Strong	
FRC	0	In formation	Weak	
ST	~	maybe	Strong	$\sim$ V <sub>loop</sub>
RFP	~	yes	Weak	$\sim$ V <sub>loop</sub>
Gun Spheromak	~	yes	None	~V <sub>gun</sub>

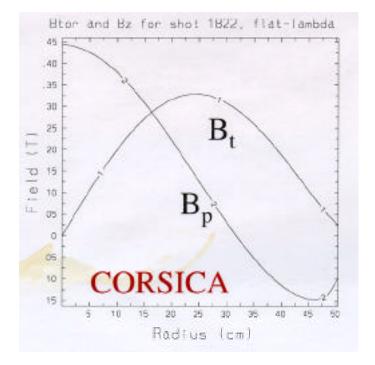
<sup>\*</sup> l is the pole number

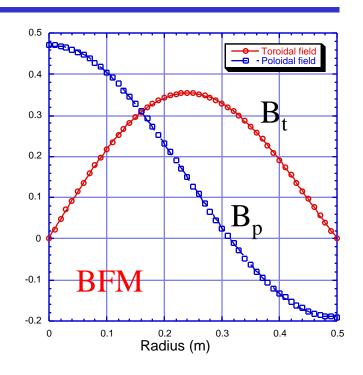
•Is it useful to compare devices with similar helicity?

# Spheromak equilibrium has simple Bessel function fields: epitomises relaxation.

•Solution to  $\times B = B$  for the spheromak:

$$\vec{B}_0 = B_0[J_0(r)\hat{z} + J_1(r)]$$





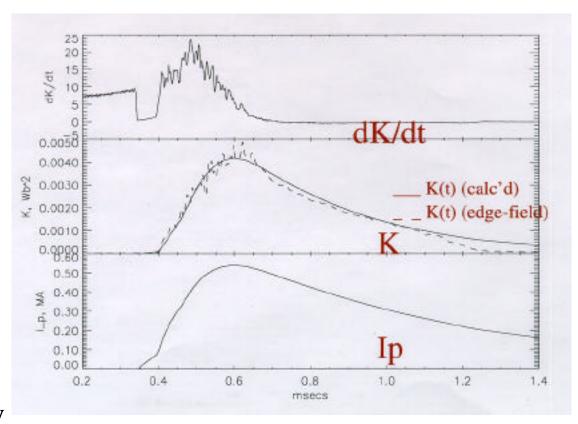
•The best 2D resistive MHD simulation gives good agreement with BFM!

### Helicity balance can be used as a good model to predict spheromak evolution.

•The paradigm for relaxation physics is 'helicity-conservation':

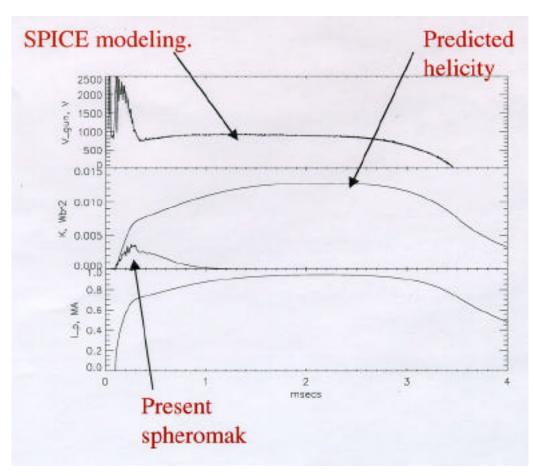
$$\frac{K}{t} = \frac{-K}{K} + 2V_{inj} \quad _{inj}$$

•The magnetic energy and plasma current can be calculated from the helicity evolution.



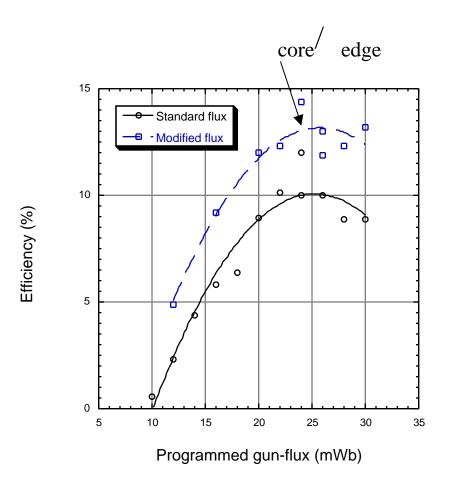
• Good agreement is found between predicted and measured helicity evolutions in SSPX.

#### Helicity balance predicts the evolution of future experiments.



- •Predictions for future experiments, and supports the Fowler/Hua build-up model[1].
- •Energy balance is complimentary: physics is entailed in the decay time.
- •The predicted evolution uses a helicity decay time,  $_{\rm K}\sim600\mu {\rm s}$ . Future calculations will give  $_{\rm K}(t)$ .

#### Driving closer to Taylor state can improve efficiency.

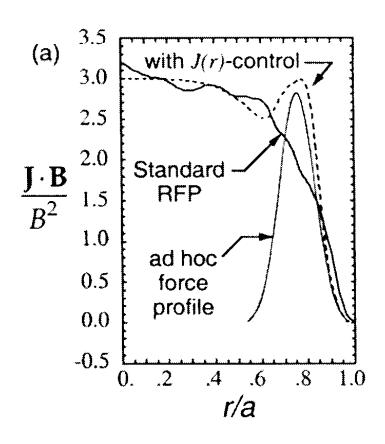


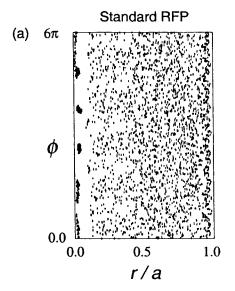
- •Drawing more flux from injector reduces the edge (~J/B) closely matches spheromak.
- •Also increases injection rate:

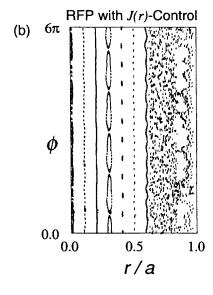
$$\dot{K} = 2V_{inj}$$
  $_{inj}$ 

•Flexible flux geometry in SSPX will allow near-Taylor state sustainment.

## Maintaining relaxed systems close to Taylor state has many benefits.

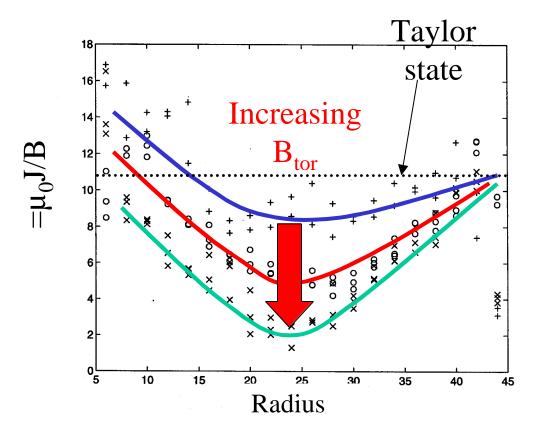






•Sustaining RFP closer to Taylor state by current profile control leads to reduced fluctuation levels, higher temperatures and better confinement.[1]

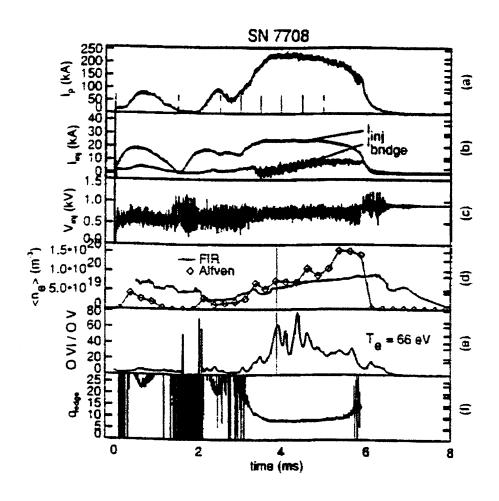
## Helicity injection into a ST with toroidal field appears to move profile away from Taylor state.



- •SPHEX-ST: With applied fields, -profile becomes far from relaxed.[1]
- •Driving away from Taylor state leads to low annular current.
- •Do strong fields inhibit relaxation?

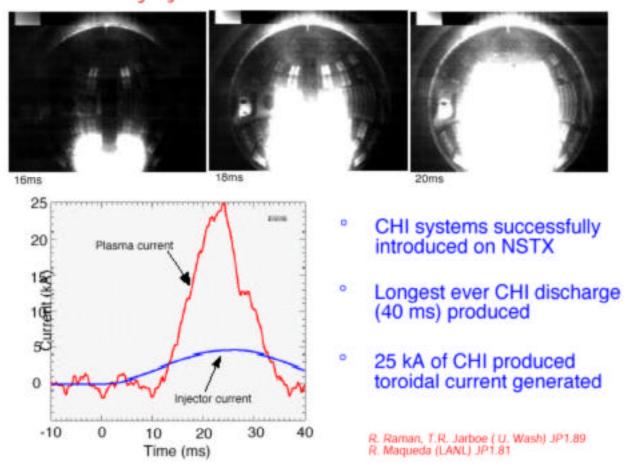
#### Some evidence for relaxation in the ST - HIT.

- •HI alone: 250kA toroidal current, 100eV (TS) measured T\_e.[1]
- •Relaxation may entail RMF-like current drive.



#### NSTX - initial HI results are encouraging - 25kA toroidal current.

#### Coaxial Helicity Injection



#### Asymmetry is a common phenomenon in helicity injected devices



- •Often the minimum energy state has a helical component.
- •RFP dynamo modes: toroidal kink modes.
- •Spheromak/HI-ST n=1 mode: kinked distortion of open flux.
- •Internal probe measurements in SPHEX reveal asymmetric equilibria [1][2].

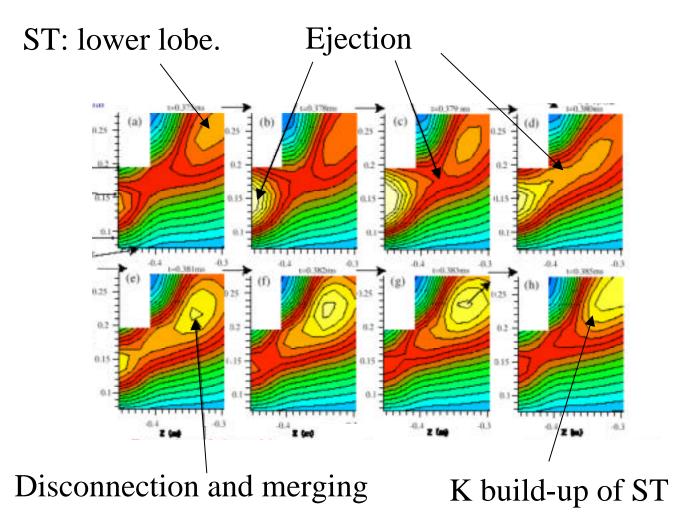
<sup>[1]</sup> Duck et al Plasma Phys. Cont. Fusion v39, p715 1997

<sup>[2]</sup> Woodruff - Thesis 1999

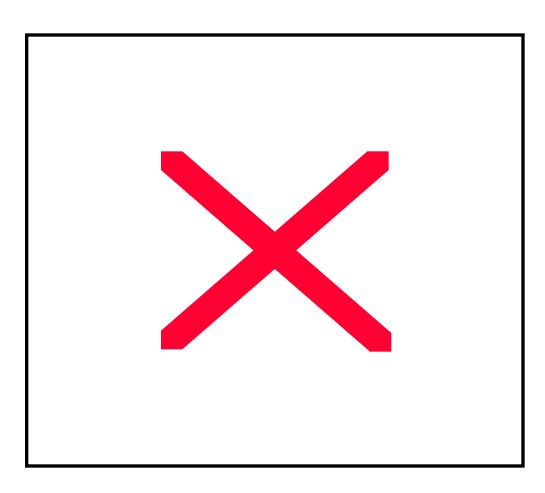
### Helicity can be 'injected' by various means: formation and current-drive.

Method	ICCs with application	K_inj 'rate'
Ohmic solenoid	ST/RFP/FRC/Spheromak	$2V_{loop}$
Beam/Wave	All	I^2
PPCD/OPCD	RFP	$2V_{loop}$
F-theta pumping	RFP	<~~>
MHD dynamo	RFP/Spheromak/ST(?)	$\langle \tilde{v} \times \tilde{B} \rangle$ . B dV
Coaxial Helicity Injection	Spheromak/ST	$2V_{\rm inj}$ $_{\rm inj}$
RMF/RMF(n=1)	ST/Spheromak/FRC	I^2
CT injection	Potentially all	K <sub>ct</sub>

# Poloidal flux contours in HIST reveal multiple CT injection - helicity injection and sustainment of ST.

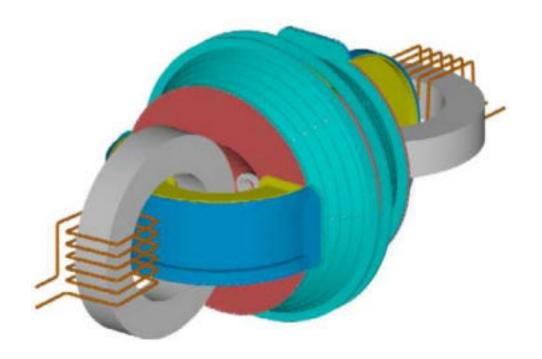


#### 'Bursting' can lead to helicity build-up and current drive in SSPX



- •Currents of 400kA can be driven by multiple plasmoid injection.
- •Strong ion heating occurs during formation [1], and could be linked to this process.

### Future devices will exploit Taylor state and helicity injection: HIT-SI, SPHERA and SPIRIT.



- [1] Jarboe et al, Fusion Technology, 36 (1), p. 85, 1999
- [2] Alladio et al, Nuclear Fusion 37(12), p1759, 1997
- [3] Yamada et al, Proc Hi-Beta Wrkshp, Seattle, 18-20 March 1998

- •HIT-SI will enable a steady inductive supply of helicity to be delivered to a spheromak.[1]
- •SPHERA aims to produce tokamak configurations with a plasma central column.[2]
- •SPIRIT will allow multiple configurations to be formed, including FRC, spheromak, and low aspect-ratio RFP.[3]

### Conclusion: relaxed/partially-relaxed plasmas can benefit from a description entailing helicity.

- •Descriptions of equilibrium, evolution and current drive are provided.
- •Sustaining close to Taylor state leads to efficiency gains in the RFP could also be realized in the Spheromak and ST.
- •Relaxation processes are still a subject of great interest in the spheromak and ST.
- •The future of HI both as a means to form and sustain plasmas looks quite intriguing.